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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1391

ICING PROPERTIES OF NONCYCLONIC
WINTER STRATUS CLOUDS

By William Lewis, U. S. Weather Bureau

Ames Aeronautical Laboratory
Moffett Field, Calif.



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SUMMARY

Measurements of the vertical distribution of liquid water concentration and drop size have been made in winter stratus clouds in the absence of significant cyclonic or frontal activity. The observations indicate that the clouds are formed by turbulent mixing of the lower layers of the atmosphere, resulting in a region of constant specific humidity and adiabatic lapse rates. Calculations based on these characteristics were used to construct a graph which gives the liquid water concentration in terms of the temperature at the cloud base and the height above the base. In clouds from which no snow was falling, the measured values were in good agreement with those given by the graph. Snowfall was found to deplete the liquid water content especially in the lower part of the cloud layer, causing dissipation of the cloud from the base upwards.

The technique used for measuring drop sizes gives only the maximum size present and hence only minimum values for the number of drops. The results obtained are consistent with the theory that the number of drops per unit volume is constant within the cloud and the size distribution is more uniform in the upper layers.

Reasonable assumptions concerning maximum cloud thickness lead to the conclusion that the liquid water concentration at temperatures below freezing in noncyclonic stratus will not exceed 1.5 grams per cubic meter.

¹This report was prepared by Mr. Lewis in collaboration with the staff of the Ames Laboratory during a period of active participation by Mr. Lewis in the NACA icing research program.

INTRODUCTION

In order to establish a rational basis for the efficient design of thermal ice-prevention systems for airplanes, the Ames Aeronautical Laboratory of the National Advisory Committee for Aeronautics has undertaken an experimental investigation of the meteorological conditions conducive to the formation of ice on aircraft. A C-46 airplane has been equipped to measure free water, air temperature, and drop size in clouds. The results of the free-water and temperature measurements made during the 1943-44 season have been reported in reference 1.

The principal physical factors determining icing conditions are temperature, liquid water concentration, and drop size. The meteorological conditions of icing involve the distribution of these physical variables within clouds and precipitation of various types in various synoptic weather situations. This report presents results of observations of the distribution of liquid water concentration and drop size in winter stratus clouds in the absence of significant frontal or cyclonic activity. The observations were made near Minneapolis, Minn., in November and December, 1944.

APPARATUS AND METHOD

Air temperature and free water concentration were measured essentially by the same methods discussed by Hardy in reference 1. The remarks contained therein apply equally to the present investigation except that the dew-point meter has been modified to function as an automatic instrument. The method consisted of measuring the dew point of a sample of air which had been heated enough to evaporate all the free water. The difference between this dew point and the free-air temperature as measured with a mercury-in-glass thermometer, corrected for kinetic heating due to the speed of the airplane, was used to calculate the free water concentration.

Drop sizes were measured by means of a cylinder which was covered with blueprint paper and extended for a few seconds into the air stream with its axis normal to the direction of motion. A 4-inch-diameter cylinder was chosen since it can be used to measure drop diameters from 8 to 35 microns at speeds from 120 to 200 miles per hour. The blueprint paper was exposed to light just prior to use to make it

sensitive to small amounts of moisture. The impingement of drops on the cylinder caused wetting of a strip along the windward side which was identified by a change of color of the blueprint paper. According to the theory of the movement of drops around a cylinder as developed by Glauert (reference 2), the width of the area of impingement of drops is a function of the airspeed, the drop size, and the diameter of the cylinder. Data from Glauert's paper, corrected for deviations from Stokes' law, were used to draw a set of curves which give the drop diameter directly from the width of the area of impingement and the airspeed. These curves determine the diameter with an accuracy of about ± 2 percent; however, it must be kept in mind that these results contain any errors that may be present in Glauert's data. This method gives only the size of the largest drops that are present in sufficient quantity to affect the blueprint paper and tells nothing directly about the size distribution.

The quantity used in this report to represent drop size is the mass of one drop times 10^8 . This quantity, which is designated W_{100} , represents the liquid water concentration in grams per cubic meter of a cloud having 100 such drops per cubic centimeter. If the drops are all the same size, the number of drops per cubic centimeter is obtained by dividing the measured liquid water by W_{100} . If the size distribution is not uniform, the calculated number of drops will be too small.

The data were collected by flying the airplane in a circle at constant rate of climb from a point in the clear air below the cloud (when possible) to a point above the cloud top. Readings of all instruments were taken frequently during the climb and the resulting values were plotted against altitude. Similar readings were made in descent through the cloud layer.

METEOROLOGICAL DISCUSSION

The temperature and dew-point curves obtained as previously outlined support the view that these stratus clouds are formed at the top of the surface turbulence layer at 2000 to 4000 feet above the ground as a result of the downward eddy flux of heat and upward flux of moisture. Once condensation has begun, radiation from the upper surface of the clouds provides additional cooling, which causes the cloud layer to

increase in thickness and intensifies the vertical mixing which maintains adiabatic lapse rates from the ground to the top of the cloud. The radiational cooling of the cloud layer also serves to establish and maintain a sharp temperature inversion at the cloud top which establishes an upper limit to the turbulent and convective mixing and thus prevents loss of moisture to the drier layers aloft. The structure of this noncyclonic winter stratus is very similar to that of the summer stratus of the Pacific and Gulf coasts.

Since the moist layer is characterized by nearly complete adiabatic mixing, it follows that the liquid water concentration at any point in the cloud may be calculated by considering an air parcel lifted adiabatically from the condensation level. The free water is found by taking the change in saturation mixing ratio, which represents the amount of condensed water in grams per kilogram of dry air and can be read from a pseudoadiabatic chart, and multiplying it by the number of kilograms of dry air per cubic meter of saturated air to obtain the liquid water concentration in grams per cubic meter. The results of such calculations when the condensation pressure is taken as 980 millibars (948 ft, pressure altitude) are presented in figure 1. A similar chart (fig. 2) was prepared for a condensation pressure of 850 millibars (4780 ft, pressure altitude). The two charts give the same values for liquid water concentration to within 0.1 gram per cubic meter for all values of condensation temperature below freezing and cloud thickness less than 4000 feet. This shows that the actual elevation of the cloud base, or condensation level, is of little importance and the significant factors are the temperature at the cloud base and the height above the cloud base.

According to the generally accepted theory of atmospheric condensation as presented by Petterssen (reference 4) and Simpson (reference 5), the number of drops per unit volume in a cloud is determined by the number and size distribution of the hygroscopic nuclei present and the rate of cooling at the time of condensation. If cooling is very slow, only slight supersaturation will occur and only the largest nuclei will become effective as centers of condensation, while more rapid cooling produces a higher degree of supersaturation and a larger number of nuclei become active. As cooling continues, the number of drops remains constant while the liquid water concentration and drop size increase together. Calculations made by Petterssen (reference 4) using an equation developed

by Houghton show that as the drops grow the size becomes more uniform. These facts suggest, therefore, that the use of the cylinder method in the determination of drop size will produce data which are a good approximation of the average drop size at the cloud top, but which indicate drop sizes considerably larger than the average near the base of the cloud. This results in values of N , the number of drops per cubic centimeter, which are approximately correct in the top of the cloud and too small in the lower portions. Assuming that the actual number of drops per unit volume is constant throughout the cloud, the value of N calculated for the upper part may be used with the measured values of liquid water content for the entire layer to obtain a good approximation of the average drop size.

RESULTS AND DISCUSSION

Representative temperature, dew point, liquid water, and drop-size data as obtained during four flights through non-cyclonic stratus clouds are presented in figure 3. The values of W_{100} obtained from individual observations have been plotted and are represented by a faired curve. Also presented in figure 3 are the droplet diameters in microns and values of N , both of which have been computed from the faired curve of W_{100} and the average drop diameter as calculated on the assumption that the value of N measured at the top of the cloud is the true value for the entire cloud layer.

During flight 126 (fig. 3(a)), the cloud base was very indefinite and the lapse rate in that vicinity was less than the adiabatic, indicating incomplete mixing. The values of liquid water concentration, determined from figure 1, were lower than the measured values near the top of the cloud and higher near the base. The differences, however, are not larger than the uncertainty of measurement. The increase of N from the base to the top of the cloud layer may be interpreted either as a real increase in number of drops or a more homogeneous size distribution in the cloud top. The data are not inconsistent with the drop-size theory given above but do not give positive proof of its correctness.

The cloud base was not reached on flight 127 (fig. 3(b)) as it was below the lower limit of safe flight altitude, but it was approximately determined from surface reports as at about 1200 feet altitude. This gives a total cloud thickness

of about 1000 feet and a calculated maximum liquid water concentration of 0.39 grams per cubic meter as compared with 0.43 as measured with the dew-point instrument. In this flight the data indicate a nearly uniform number of drops but data are available only for the upper half of the cloud.

The air-temperature and dew-point values were much lower (10° F to 20° F) on flight 123 (fig. 3(c)) than on the previously discussed flights. At these temperatures it is likely that the deposit on the mirror of the dew-point instrument was composed of frost instead of dew. Since a cloud containing liquid water drops is assumed saturated with respect to liquid water in calculating the free-water from the dew-point data, the dew point rather than the frost point must be used. The dew-point meter readings were therefore corrected by subtracting the difference between the saturation temperatures with respect to ice and water. This flight was conducted after snow had begun to fall from the cloud layer. In order to interpret the data, then, consideration must be given to the effect of snow on the liquid water concentration in the clouds and on the accuracy of the measurements.

The Effect of Snow on the Measurement of Liquid Water

Since the dew-point meter measures the dew point of a sample of air into which all the free water has been evaporated, the free-water content values obtained in this way represent the total of snow and liquid water unless a correction is made. This was done by assuming that all the free water measured at the altitude of the cloud base was in the form of snow and that no snow was present at the cloud top. A straight line was drawn between these two points to represent what the dew point would have been if no snow had been present. This dew-point curve was used in calculating the liquid water concentration.

The Effect of Snow on the Liquid Water Content

It is not known at present whether snowflakes are formed as a result of the freezing of water drops or by deposition of vapor on separate nuclei but in either case it is likely that they form with somewhat greater frequency in the upper portions of the cloud where the temperature is lower.

Wherever they form, they grow rapidly, due to the vapor pressure difference between ice and water, and fall through the cloud as they grow. This results in a higher concentration of snowflakes and more rapid depletion of liquid water in the lower layers of the cloud, which results in raising the cloud base. During the early stages of this process, the liquid water concentration near the top of the cloud where there has been little depletion may be considerably greater than would be expected from figure 1, since the cloud base no longer represents the mixing condensation level. This flight is an example of such a situation. The liquid water concentration is only 0.51 gram per cubic meter as indicated by figure 1, while the measured value is 0.73.

The drop sizes observed on this flight also are consistent with the idea of a uniform number of drops with a nonuniform-size distribution in the lower layers.

Snow had been falling for several hours previous to flight 130 (fig. 3(d)) and all the liquid water had turned to snow except for a thin layer in the top of the cloud. The clouds broke up soon after the flight. The liquid water and drop-size data show that the last remnants of liquid water in a cloud which turns to snow are in the topmost layer.

Since noncyclonic stratus clouds are formed within the surface turbulence layer, the thickness of this layer sets an upper limit to the thickness of the cloud layer. The highest stratus top encountered was at an altitude of 5300 feet which was about 4500 feet above the ground. It is believed that this is about the upper limit of the height of the tops of clouds of this type. The maximum thickness observed was 2400 feet. There is much observational evidence to support the view that very low bases are seldom encountered in stratus when the tops are relatively high. It seems reasonable then to assume a case with a top 4500 feet above the ground and a layer 3000 feet thick as representing a good approximation to the most unfavorable condition likely to be met. Figure 4 shows the relation between liquid water concentration and temperature at the top of a 3000-foot layer. This shows a water content of 1.5 grams per cubic meter at 32° F, which is the highest that is likely to occur at freezing temperatures. It should be noted that the formation of snow is much more likely at temperatures below 15° F, making the existence of thick water clouds less likely at these temperatures.

CONCLUDING REMARKS

Observations made in noncyclonic winter stratus clouds indicate that if snow is not falling, the liquid water concentration can be approximately determined from the temperature of the base and the thickness of the layer by assuming moist-adiabatic lapse rate and constant total water content within the cloud.

The observations of drop size are not inconsistent with the theory that the number of drops per unit volume is constant throughout the layer and the size distribution is more uniform in the top than near the base.

The effect of snowfall is a progressive depletion of liquid water starting at the cloud base and continuing until only a thin layer of liquid water remains in the top of the cloud.

Calculations based on reasonable assumptions concerning maximum cloud thickness show that the liquid water concentration in noncyclonic stratus clouds is not likely to exceed 1.5 grams per cubic meter at temperatures below freezing.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif., June 1947.

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2. Glauert, Muriel: A Method of Constructing the Paths of Raindrops of Different Diameters Moving in the Neighborhood of (1) A Circular Cylinder, (2) An Aerofoil, Placed in a Uniform Stream of Air; and A Determination of the Rate of Deposit of the Drops on the Surface and the Percentage of Drops Caught. R. & M. No. 2025, British A. R. C., 1940.

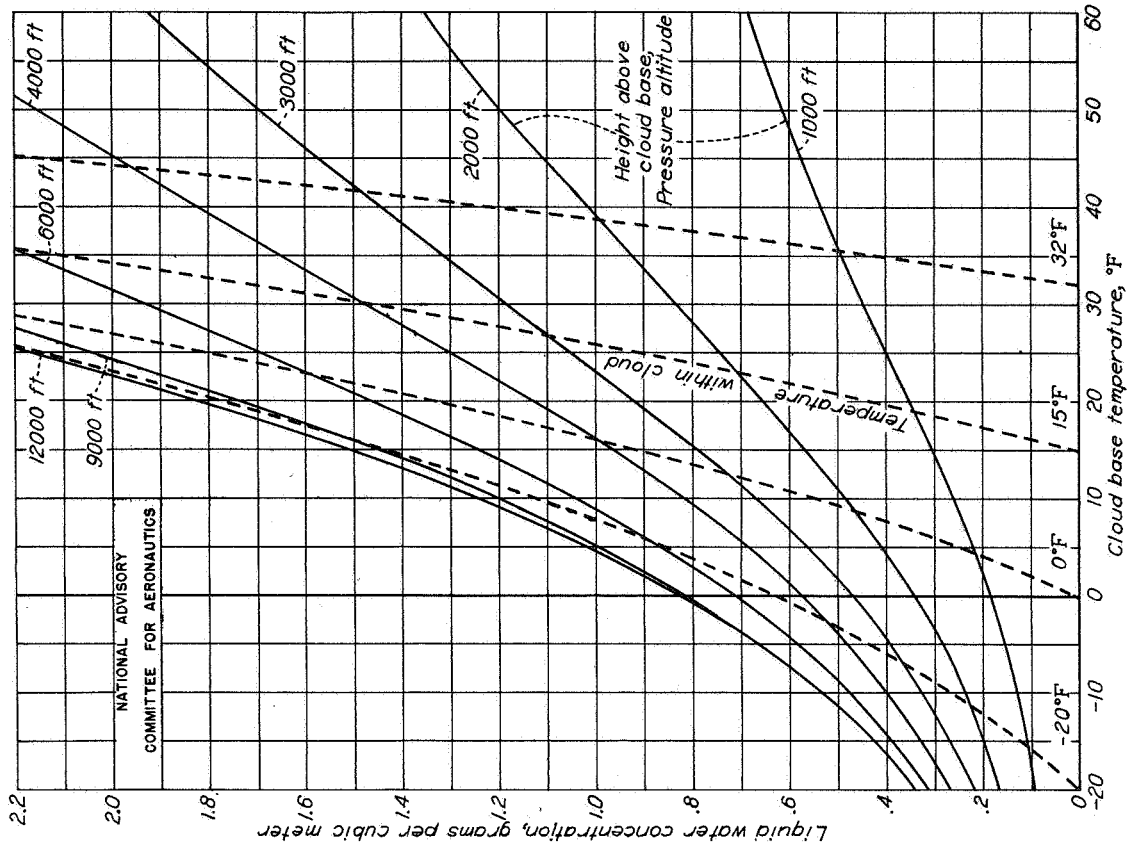


Figure 2.- Liquid water concentration in clouds formed by adiabatic lifting. Cloud base at 4780 feet pressure altitude.

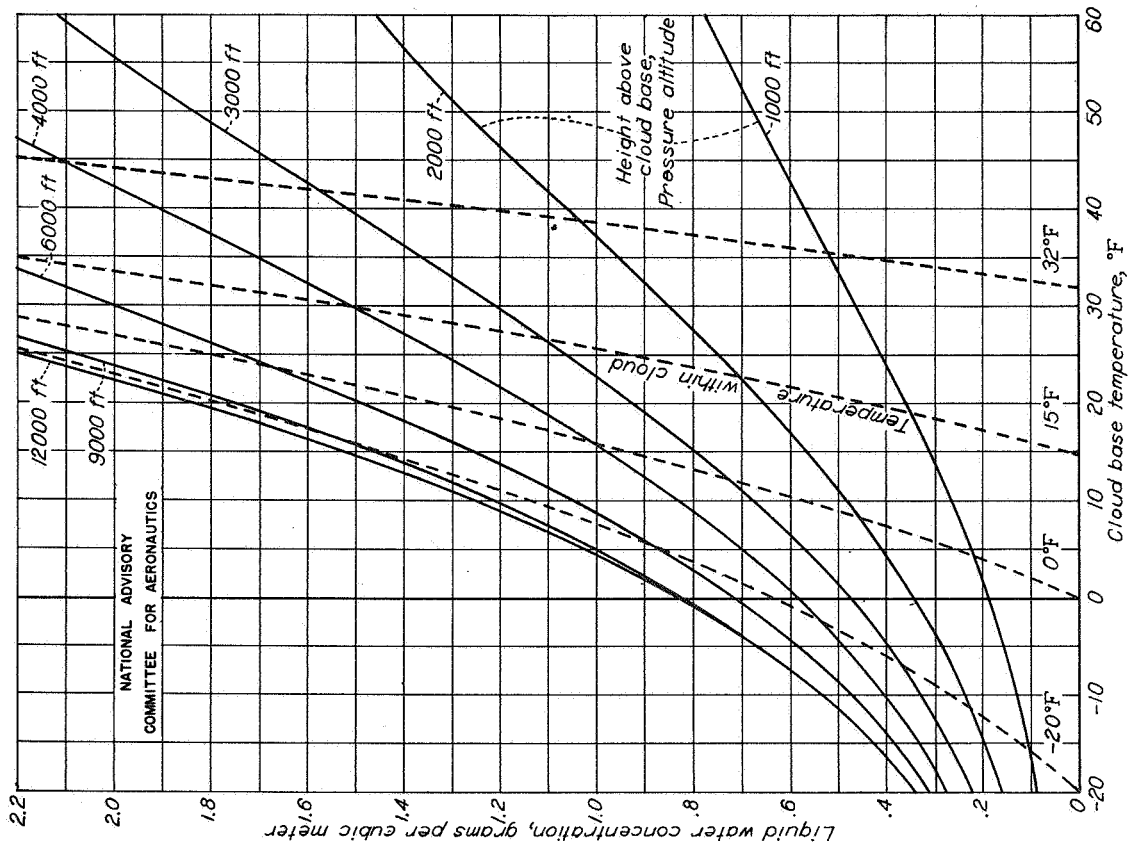
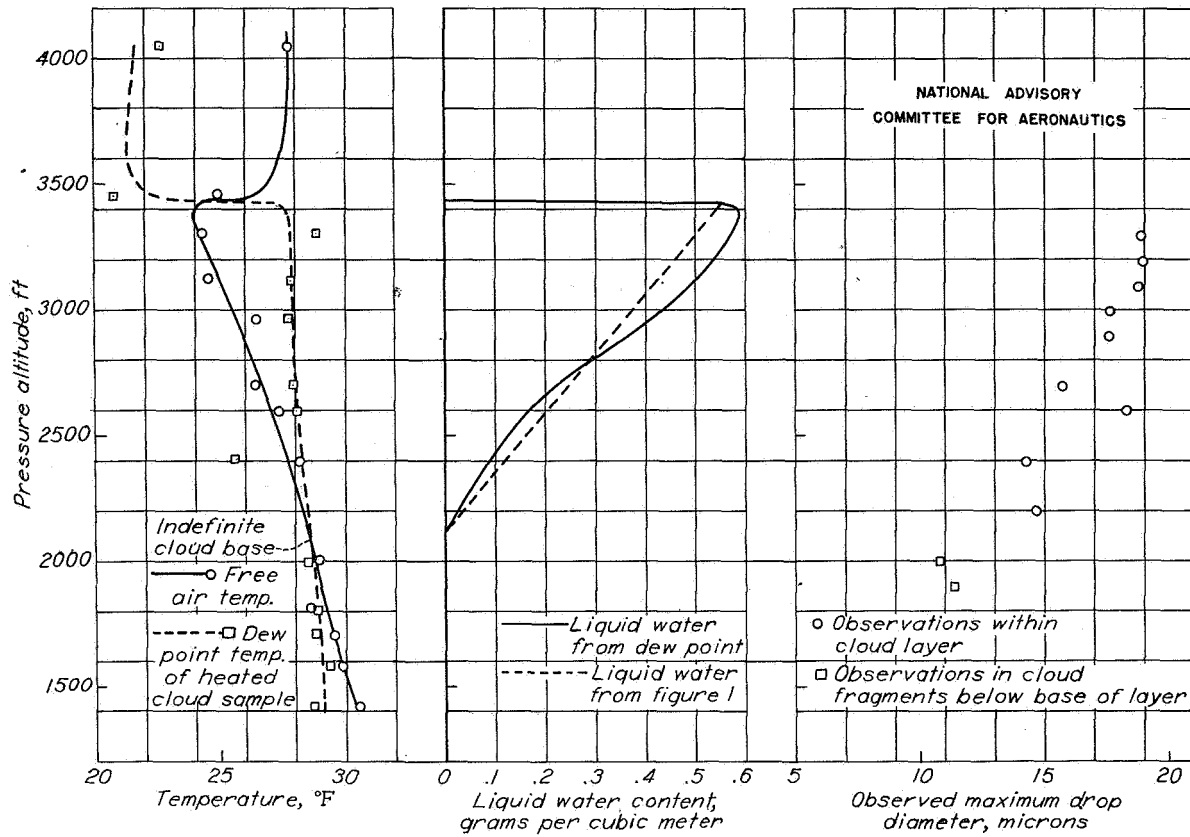
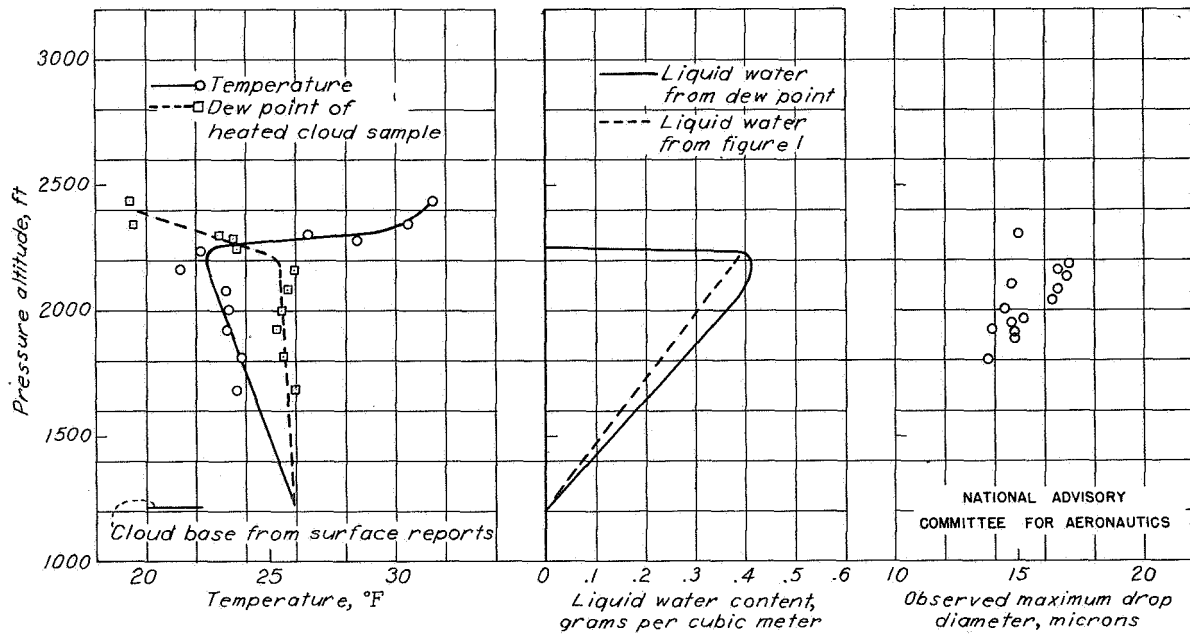


Figure 1.- Liquid water concentration in clouds formed by adiabatic lifting. Cloud base at 948 feet pressure altitude.



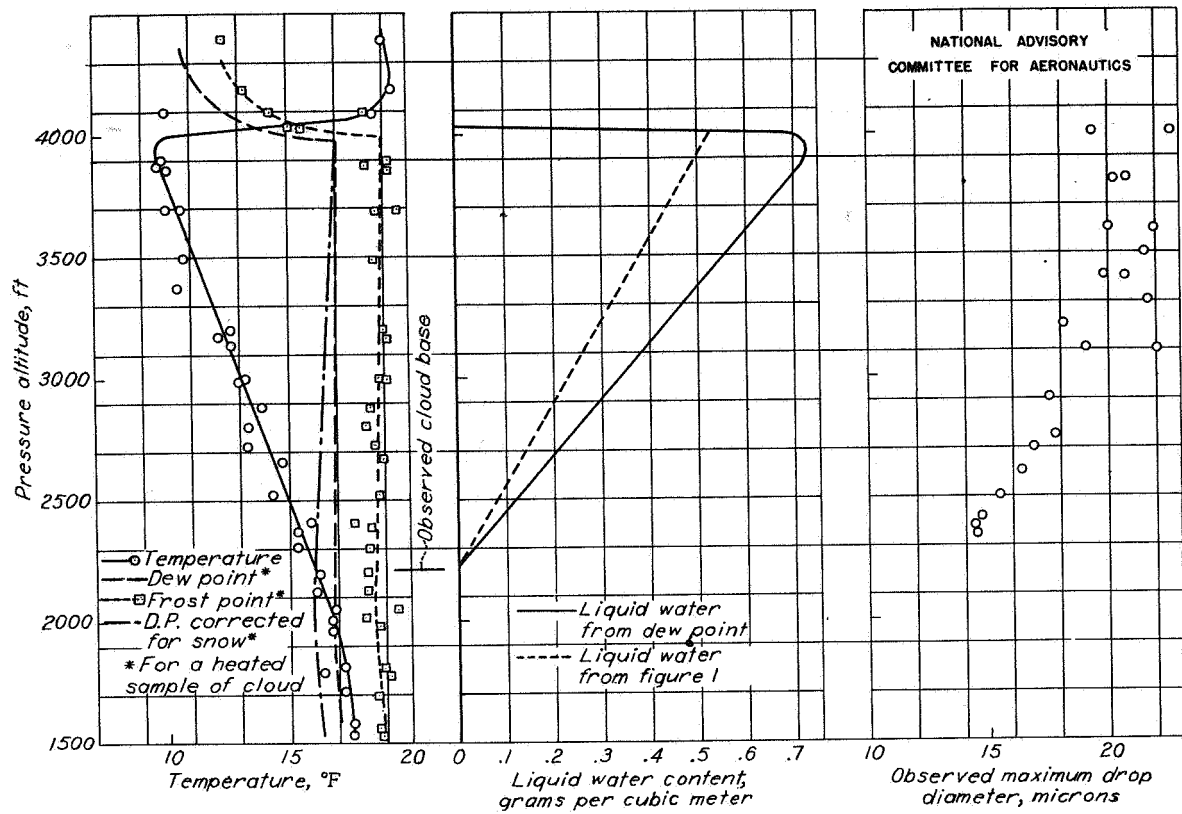
(a) Flight 126.

Figure 3.- Meteorological data in noncyclonic stratus clouds.



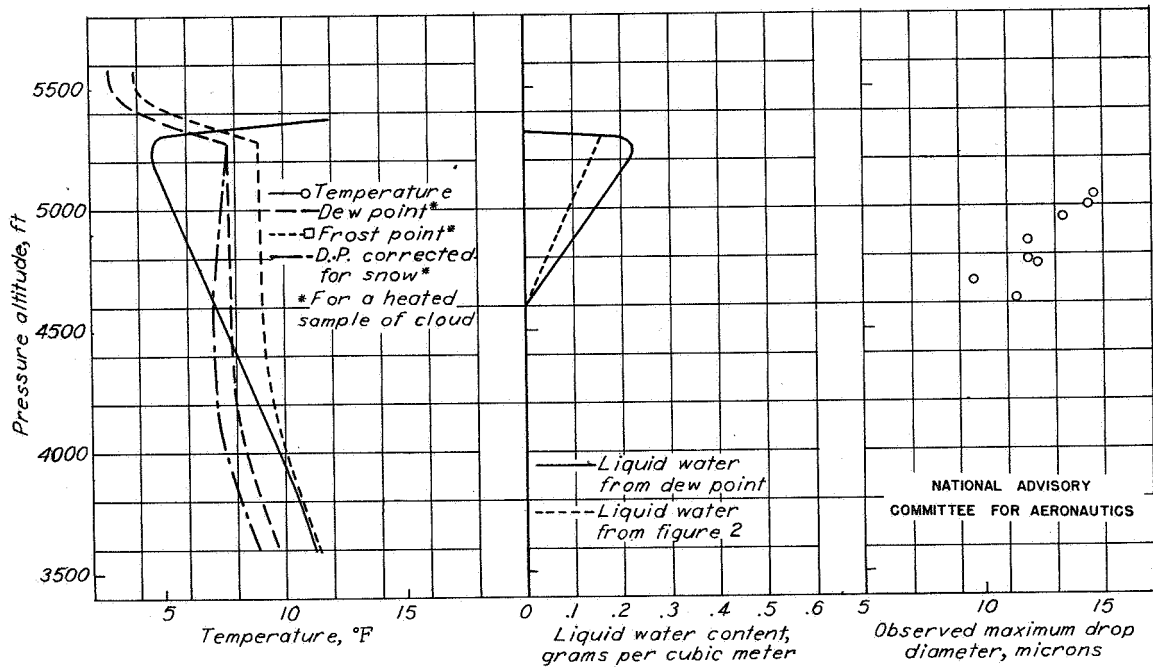
(b) Flight 127.

Figure 3.- Continued.



(c) Flight 123.

Figure 3.- Continued.



(d) Flight 130.

Figure 3.- Concluded.

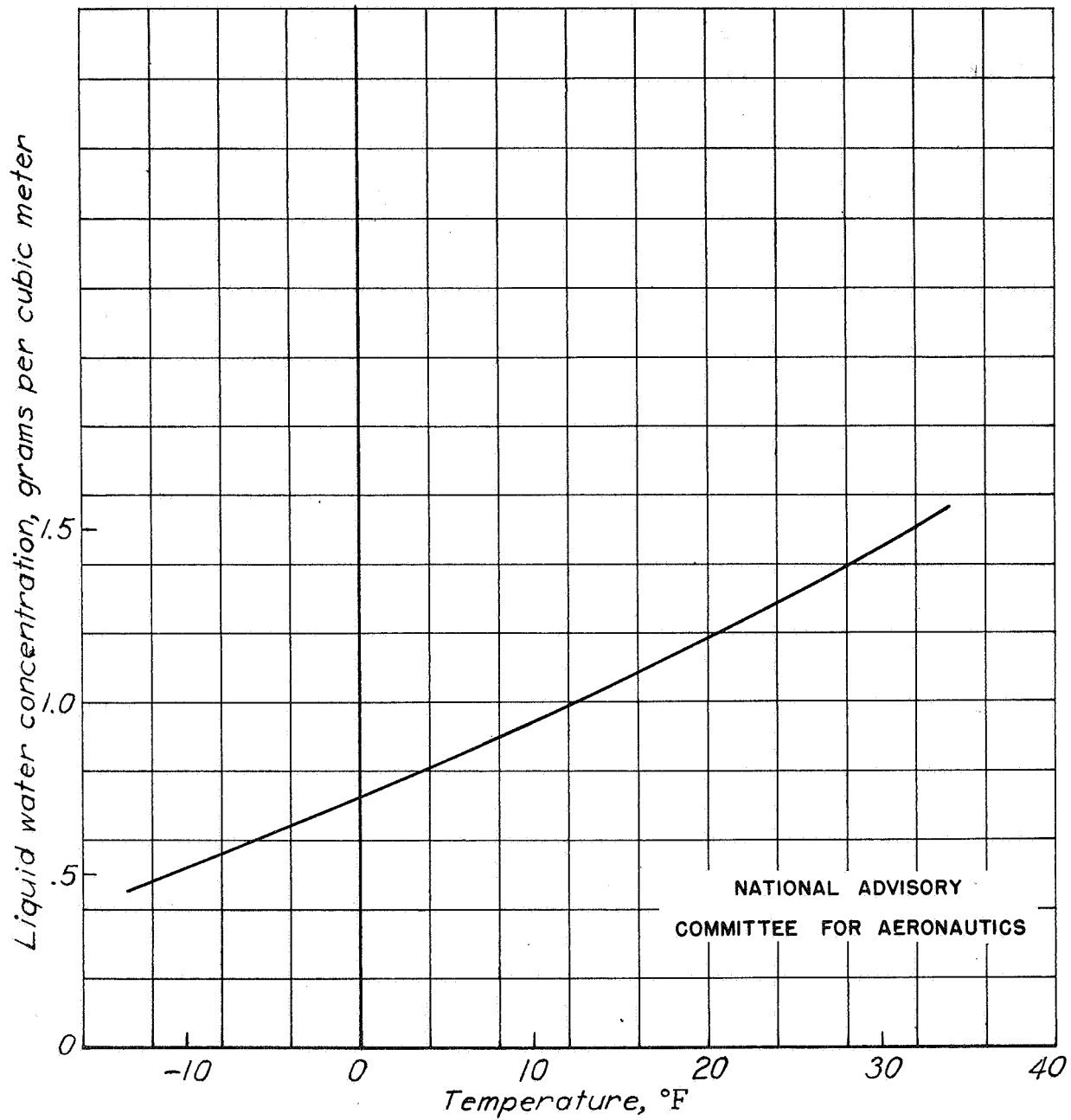


Figure 4.- Conditions to be expected at the top of a 3000-foot cloud layer. Representing the probable maximum intensity of icing conditions in noncyclonic stratus clouds.